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Effects of atmospheric CO_2 concentration on soil-water retention and induced suction in vegetated soil

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ABSTRACT

Current atmospheric CO_2 (400 ppm) is increasing 2 ppm annually and might reach up-to 1000 ppm by year 2100 due to global climate change. Different plant growth was observed under elevated CO_2 in the previous studies. However, plant induced soil suction besides plants growth due to increasing atmospheric CO_2 concentration in heavily compacted soil remain elusive. The objective of this study is to quantify transpiration and evapo-transpiration induced soil suction by *Schefflera heptaphylla* in heavily compacted soil under different atmospheric CO_2 concentration. Three replicates of the plant were grown, and their characteristics were measured under 400 ppm and 1000 ppm CO_2 concentration for three months. Leaf area index of plants decreased by 35% under 1000 ppm CO_2 concentration due to soil nitrogen scarcity which impedes the plants ability to metabolize increased atmospheric CO_2 concentration. Despite having LAI of 0.5–0.7, plant induced suction decreased by 10–25 kPa during transpiration and evapo-transpiration test under 1000 ppm CO_2 concentration. Although a strong positive linear correlation (R^2 = 0.8–0.9; *P*-value < 0.1) of LAI and root-shoot biomass ratio with induced peak soil suction under 400 ppm CO_2 concentration, a weak linear correlation (R^2 = 0.6–0.8; *P*-value > 0.1) of the same plant traits under 1000 ppm CO_2 concentration was observed. This is because leaves cannot open stomata wide enough to transpire more water when they absorb more CO_2 from the atmosphere resulting in soil suction reduction. This implies that the effects of atmospheric CO_2 concentration on plant induced soil suction must be considered in vegetated soils.

1. Introduction

Effects of the increasing atmospheric CO_2 concentration on plants have been quite important for forest management, botany, agronomy and water management in agricultural research. Previous botany and agricultural studies found increased root and shoot growth across many plant species under elevated atmospheric CO_2 (Rogers et al., 1996; Bernacchi et al., 2000; Prior et al., 1994). In contrast, elevated CO_2 effects varied among different plants (based on photosynthesis and carbohydrate storage) i.e., 60% of the studied plants showed increased root-shoot ratio (Rogers et al., 1996). A functional-structural (FS) plant model is presented by Fourcaud et al. (2008) (Fig. 1), a schematic representation of interactions between plant and its environment which considers physiological processes in organs (i.e., water absorption by roots, transportation by stem, transpiration and photosynthesis by leaves). Based on this model, plant growth is driven by basic input elements to the plant (i.e. C, N, P, K) and used by organs (i.e. leaves, roots etc. known as sinks) within 3-D architecture of plant (Fig. 1), considering output or losses. Input, investment and output variables are spatially and temporally under environmental control, i.e., both climate and soil, and variables can interact with and influence each-other. Due to climatic influence, plants displayed reductions in stomatal conductance, which also reduced their transpiration rate (Wullschleger and Norby, 2001; Dugas et al., 2001; Dong-Xiu et al., 2002) and evapo-transpiration rate under elevated CO_2 concentration (Dijkstra et al., 1999; Conley et al., 2001; Hungate et al., 2002). In contrast, differences in transpiration rate were not significant when atmospheric temperature increased (Apple et al., 2000; Lewis et al., 2002) and differences in evapo-transpiration rate also reduced over time (Grunzweig and Korner, 2001) or in different soil (i.e., calcareous soil) (Bucher-Wallin et al., 2000). However, some plants responded to elevated atmospheric CO_2 concentration while some plants did not respond.

Research on the vegetation effects on slope stability and landfill cover has become more widespread in the last few decades (Smethurst et al., 2015; Sinnathamby et al., 2013). Positive influence of vegetation (hydrological effects) is now more recognized. This is due to an increase in plant-induced soil suction upon evapo-transpiration which leads to an increase in soil shear strength and decrease in water permeability

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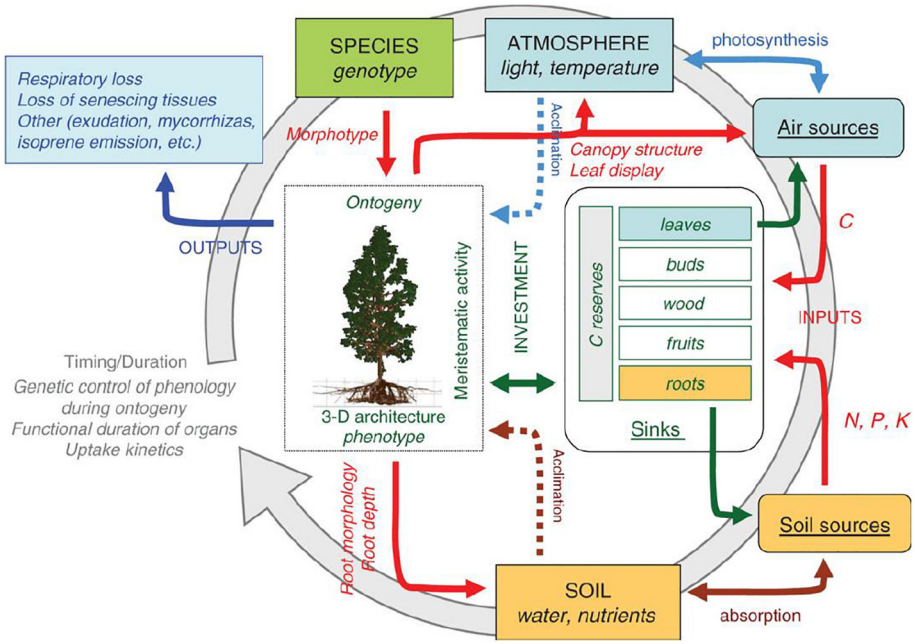

Fig. 1. A schematic representation of interactions between a plant and its environment (Functional-structural plant model). (Fourcaud et al., 2008).

(Ng and Menzies, 2007; Ng and Leung, 2012). Vegetation is also recognized as an effective way for mitigating soil surface erosion (Shen et al., 2017). Previous studies have shown that some plant traits such as- leaf area index (LAI) (Ng et al., 2016) and root-shoot biomass ratio (Boldrin et al., 2017) have a linear positive correlation with plant induced soil suction. Since atmospheric CO_2 concentration is increasing 2 ppm annually due to global climate change (Keeling and Whorf, 2005) and might reach 500–1000 ppm by year 2100 (IPCC, 2013), it might affect plants and hence plant induced soil suction which is crucial for slope stability and transient seepage analyses. Furthermore, there is a lack of understanding whether the previous correlations between plant traits and induced soil suction is still valid under elevated atmospheric CO_2 concentration. Moreover, in addition to 3-D plant architecture as an output of FS plant model (Fig. 1), plant-induced soil suction, volumetric water content and correlation of plant traits with suction due to uptake of more CO_2 from the atmosphere were not considered in heavily compacted soil. These need to be considered from an engineering point of view to ensure proper design of vegetated slopes, road and railway embankments and landfill covers with respect to climate change and increasing atmospheric CO_2 concentration.

In this study, a laboratory experiment was conducted to quantify and compare the magnitude and distribution of suction induced by transpiration and evapo-transpiration of *Schefflera heptaphylla*, in silty sand under current (400 ppm) and elevated (1000 ppm) CO_2 concentration. In addition, plant traits (e.g., LAI, leaf number, shoot and root length, shoot and root biomass) were quantified and correlated with plant induced soil suction as well as soil-water retention curves were also established.

2. Materials and methods

2.1. Test plan

In this study, two test series were conducted. First and second test series were intended to grow plants in heavily compacted soil under 400 ± 50 ppm and 1000 ± 50 ppm CO_2 concentration and to investigate transpiration and evapo-transpiration induced soil suction and volumetric water content (VWC). First series is a reference test since the current atmospheric CO_2 concentration is 410 ppm (Dlugokencky and Tans, 2018). Second series is to represent a scenario where CO_2 concentration might reach 500–1000 ppm by year 2100 (IPCC, 2013). Bare soil was also tested in both test series. Transpiration and evapo-transpiration induced soil suction was influenced by plant transpiration (covering the soil surface) and plant-soil system, respectively. Atmospheric CO_2 enrichment generally reduces leaf stomatal conductance in most plants, which reduces the amount of water they transpire. (de Boer et al., 2011; Lammertsma et al., 2011) At the same time, it often stimulates or inhibits the production of leaf area (Bernacchi et al., 2000; Tingey et al., 1996), which tend to increase or reduce the amount of water they convey to the atmosphere (Kelliher et al., 1995). Moreover, the stimulated or reduced leaf area shades or exposes more of the underlying ground from the direct rays of the sun, which could increase or reduce the amount of water evaporated from the soil. Hence, it is not immediately clear what the net effect of these several competing phenomena would be with respect to evapo-transpiration or the loss of water from the entire soil-plant system. Besides, Garg et al. (2015) observed 3%–47% difference between transpiration and evapo-transpiration induced soil suction. Therefore, in this study both transpiration and evapo-transpiration induced drying tests were conducted to investigate atmospheric CO_2 effect on plant induced soil suction by these two processes.

2.2. Test set-up and instrumentation

Fig. 2 shows the schematic setup of a vegetated test box. Four boxes were constructed with cross-section area of 300 mm × 300 mm and a height of 350 mm. Soil was compacted in boxes up-to 280 mm depth and an individual tree was transplanted at the centre of three boxes. Side boundaries were impermeable, free drainage was allowed through 5 mm diameter holes at the bottom of the box and top boundary was exposed to the environment. Three miniature tip tensiometers at depths of 30 mm, 80 mm and 140 mm (within initial root depth zone) and one tensiometer at depth of 210 mm were installed just below the tree at the centre of box. The measurement range of suction is limited by water cavitation in tensiometer when negative pore-water pressure in soil approaches 80–90 kPa (Fredlund and Rahardjo, 1993). One soil moisture probe (SM-300) was installed at 80 mm depth right next to the tensiometer to monitor VWC, to check the measurements of suction against VWC and to investigate the effects of CO_2 on root growth which might affect soil water retention behaviour. Since two moisture probes

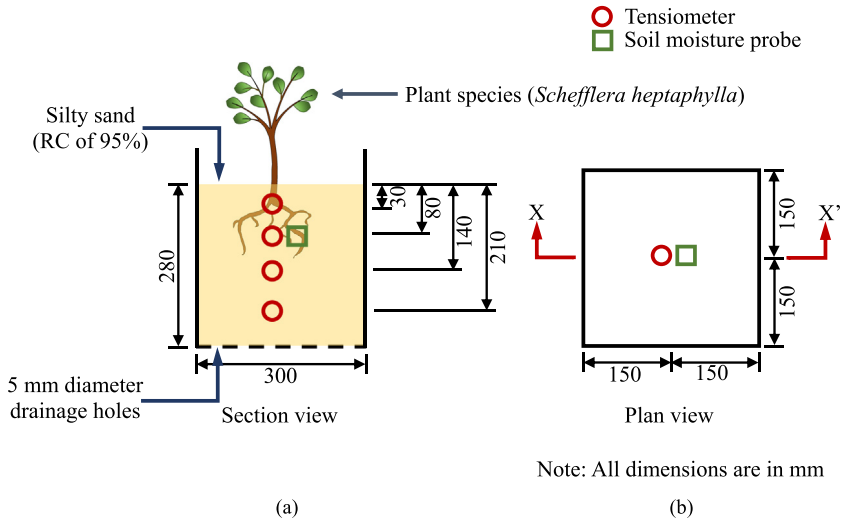

Fig. 2. Typical schematic setup and instrumentation of a tree-vegetated test box in (a) cross section view X–X' and (b) plan view.

should be installed 100 mm apart and the initial root depth was around 130–140 mm, middle point of the root length (80 mm) was chosen to establish the SWRC.

The tests were conducted in a growth chamber (Fig. 3). The inside wall of the chamber is coated with an aluminium fabric so that outside and inside environment of the chamber cannot affect each other. One 600-Watt light (550–690 nm of wavelength) was established at the centre top of the chamber due to its favourable waveband range (400–700 nm) for plant photosynthesis and growth (Gates, 1980; Ng et al., 2014). A pair of light reflector wing was connected around the light to distribute the light intensity uniformly on the plants. An inline fan (720 cfm) was connected to the light through an air duct as shown in Fig. 3 where the air was flowing through the duct within the light on the top of the chamber to the outside of the chamber. Since the sealed connected duct on the top of the chamber separated the air flow by the inline fan, the air flow did not affect CO_2 concentration or the plants within the chamber. The air was flowing to avoid additional heat produced by the light to ensure that heated air can be removed outside the chamber because without the airflow the light raised the temperature to 35 ± 1 °C. With the air flow through the light, the air temperature and relative humidity was maintained at 28 ± 1 °C and 60 ± 5% inside the sealed chamber, respectively. CO_2 was supplied by a compressed CO_2 tank through a pipe inside the chamber. CO_2 concentration, temperature and humidity were monitored and controlled by a Deluxe Digital Atmosphere Controller and Sensor. Since CO_2 is heavier than air, a 3-D rotating fan was kept near the floor and the CO_2 supply pipe was kept in front of the fan so that air with CO_2 can be distributed more uniformly within the whole chamber. The chamber was sealed to prevent loss of CO_2 and to maintain an identical condition (temperature and humidity) throughout the test duration.

2.3. Soil type and sample preparation method

Soil tested in this study was completely decomposed granite (CDG), commonly found in tropical and sub-tropical regions of the world (i.e., Hong Kong and Korea). According to the Unified Soil Classification System (USCS; ASTM, 2010), CDG is classified as silty sand. Based on the results from standard proctor tests, the maximum dry density and the corresponding optimum water content (by mass) of the CDG were 1870 kg/m^3 and 12%, respectively. All the measured index properties of CDG soil are summarized in Table 1.

The CDG in each test box was compacted by moist tamping at a relative compaction (RC) of 95% (corresponding to the dry density of 1777 kg/m^3). Compacting to such a high RC is common for man-made

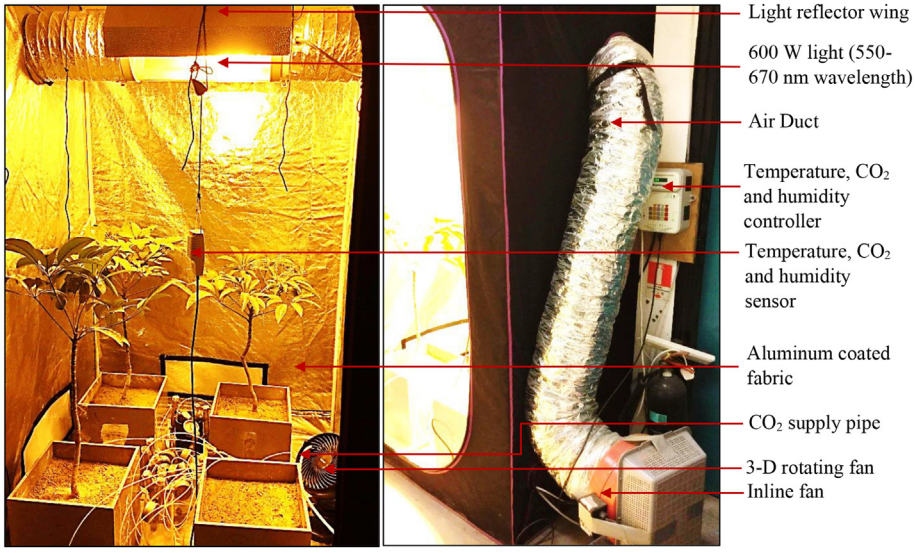

Fig. 3. Overview of the test set-up and instrumentation in the atmospheric-controlled plant growth chamber.

Table 1
Index properties of completely decomposed granite (CDG).

Index Properties	Value
Standard compaction tests	
Maximum dry density: kg/m^3	1870
Optimum moisture content: %	12
Particle-size distribution	
Gravel content (> 2 mm): %	19
Sand content (≤2 mm): %	42
Silt content (≤63 μm): %	27
Clay content (≤2 μm): %	12
D_{10}: mm	0.15
D_{30}: mm	0.7
D_{60}: mm	2
Coefficient of uniformity (D_{60}/D_{10})	13.3
Coefficient of curvature ($(D_{30})^2/(D_{60}D_{10})$)	1.6
Specific gravity	2.60
Atterberg limit	
Plastic limit: %	26
Liquid limit: %	44
Plasticity index: %	18
Unified Soil Classification System (USCS)[a]	Silty sand (SM)

[a] ASTM (2010).

slopes in countries such as the USA (TDOT, 1981) and Hong Kong (GCO, 2000). This is to design against rainfall infiltration and its induced slope instability. CDG has a field capacity of 21%, which is defined as the water content held in soil after excess water has drained away, assuming a negligible rate of water movement (Veihmeyer and Hendrickson, 1931). This water content corresponds to soil suction of 25 kPa. In each box, the CDG was compacted in 14 layers, with each spanning a height of 20 mm. Between each successive layer, the soil surface was scarified to provide better contact. An identical soil density was ensured during soil compaction and transplantation of plants in different boxes for each test series while the experimental error was observed ± 0.5% among all replicates. It was done to ensure negligible effects of soil preparation among different boxes on the experimental results.

2.4. Plant selection

The plant species investigated in this study was *Schefflera heptaphylla* (Ivy tree), which has sharp leaves and is common in many parts of Asia including southern China, Japan, Vietnam and India (Hau and Corlett, 2003). *Schefflera heptaphylla* is a small tree species. This species is selected for testing because it has significant ornamental and ecological value for slope rehabilitation and reforestation (GEO, 2011) and is drought tolerant (Hau and Corlett, 2003). Various experiments have shown that the species selected in this study, *Schefflera heptaphylla*, is able to survive and thrive under high degree of compaction i.e., 95% (Garg et al., 2015; Leung et al., 2015). For a fair comparison, trees with similar height (543 ± 33 mm), basal diameter (10 ± 2 mm) and root length (130 ± 7 mm) were selected for initial transplantation. To minimize the boundary effects of the test box on the root system, the plants with shallow root length (130 ± 7 mm) were selected and transplanted at the centre of the box covering only half (140 mm) of soil depth (280 mm).Single tree rather than several trees in each test box was studied to avoid any effects of other trees and to understand the plant-soil-atmosphere interaction due to increasing atmospheric CO_2 concentration. Three replicates were tested to consider the effects of differences of the plant characteristics on test results.

2.5. Test procedures

In first and second test series, plants were grown for three months to acclimate with soil and to investigate CO_2 effect on plant growth under 400 and 1000 ppm CO_2 concentration. The lights were turned on for 12 h and then off for 12 h to simulate day-night. Here it is to be noted that, all the experiments were conducted inside the plant-growth chamber which had identical temperature, light intensity, humidity as well as irrigation frequency, soil type and soil density were similar in all replicates. The only difference for the experiments was different CO_2 concentration to investigate the differences in plant growth due to the effects of CO_2 concentration. In both test series, the bare and vegetated boxes were subjected to a two-stage test. First stage was to apply a ponding head on the surface of boxes until (i) suctions at four depths decreased to 0 kPa and (ii) percolation through the bottom drainage holes was observed. At second stage, to quantify the effects of plant transpiration on suction responses only, the bare soil surface of vegetated boxes was covered with a laminated plastic sheet. Transpiration-induced suctions were recorded by four tensiometers. Each test was stopped when any tensiometer registered close to 80 kPa (limit of measurement range). The drainage holes at the bottom of all the boxes remained open during the monitoring period. Similar test procedures were adopted to quantify the effects of evapo-transpiration by both the bare and three vegetated boxes. The only difference was that the bare soil surface was exposed (i.e., no surface cover) to the atmosphere. In this case, suction recorded by each tensiometer in the three vegetated boxes was induced by evapo-transpiration process of the plant-soil system. In this study, additional nutrient or fertilizer was not used in the soil to prevent any osmotic suction induced due to solute concentrations in pore water (Krahn and Fredlund, 1972). Since there has been no study or data on soil suction and soil water retention behaviour affected by plant-soil-atmospheric CO_2 concentration from the engineering point of view, additional nutrient or fertilizer might complicate the interaction.

During the growth period and after the test any changes in leaf area index (LAI), shoot height and leaf number were monitored for all tree seedlings. Leaf Area Index (LAI) is a dimensionless index for a single plant and it is defined as the ratio of the total leaf area to the projected area of canopy of an individual plant on the soil surface in horizontal plane (Watson, 1947). LAI was determined by image analysis using an open source software called ImageJ (Rasband, 2011). Images of individual tree leaves were captured by a high-resolution camera and then converted to binary images, based on which the leaf area can be determined. After testing, the root length and root area index (RAI) of all the plants were determined. RAI is defined as the ratio of total root surface area for a given depth range to the circular cross-sectional area of soil in the horizontal plane (Francour and Semroud, 1992). The circular cross-sectional area of soil refers to the circular area, of which the diameter is defined by the maximum lateral spread of the root system within a given depth range. The root surface area refers to the total outside (external) surface area of all roots within a given soil volume that is defined by the cross-sectional area and the depth range. RAI is a dimensionless index that indicates the water uptake ability of roots within the root zone. The tree roots were carefully removed from the test boxes and the soil attached to the roots was washed away with great care to minimize the destruction of small lateral roots and other fragile root structures. Root length was determined as the deepest soil depth beyond which no root was found. Then, image analysis using ImageJ (Rasband, 2011) was conducted to determine RAI, following the procedures suggested by Garg et al. (2015). High-resolution images were taken 360° around the roots. All these images were combined to generate a three-dimensional (3D) image. Grids with equal pixel size (i.e. 12 pixels per unit mm of length) were superimposed on the 3D image. The total number of grids that contain roots at the given depth range was counted and hence converted into the total outside surface area of roots in mm^2. Finally, RAI at any depth within a root zone can be determined by dividing the total outside surface area of roots at a given depth by the planar cross-sectional area of soil. In this study, RAI was discretized at intervals of 10 mm. The reason to provide such a discretized RAI is to more clearly determine the distribution of root surface area, which is shown to be important for interpreting suction

Table 2
Atomic and mass concentration (%) of major nutrient elements (N, P, K) in CDG soil.

Major nutrient elements	Atomic concentration (%)	Mass concentration (%)	Required mass concentration (%) in soil for plant growth
Nitrogen (N)	0.19 ± 0.04	0.13 ± 0.03	2.8–3.7
Phosphorous (P)	0	0	0.26–0.35
Potassium (K)	0.48 ± 0.07	0.94 ± 0.13	2.5–3.5

and soil water retention curve (Garg et al., 2015; Leung et al., 2015). The RAI of plant roots at depth 30 mm, 80 mm and 140 mm are shown in Table 4 since the tensiometers were installed at these depths along the root. The biomass of shoot (stem, branches and leaves) and roots for each tree was determined. Each sample was weighed and oven-dried at 60 °C for 24 h and again weighed (0.01 g of accuracy) to determine the dry biomass (Liang et al., 1989). Then, ratio of root and shoot biomass was calculated for each plant to determine root-shoot biomass ratio and correlate them with their corresponding induced suction to investigate CO_2 effects. Here it is to be noted that, during the washing of roots, few milligrams of fine roots might have washed away with the soil which could affect the total root biomass as well as the ratio of root-shoot ratio. However, the loss of these fine roots was considered to have negligible effects on the comparison of root-shoot ratio among the replicates because insignificant amount (few mg) of loss occurred in all the replicates.

X-ray Photoelectron Spectroscopy (XPS) analysis was used to determine atomic and mass concentration of major nutrients (N, P, K) in soil essential for plant growth. Results are shown in Table 2. Carbon (C) content was also measured in soil by XPS analysis before transplantation and after three months of plant growth. This is to investigate carbon input from plants to soil under 400 and 1000 ppm CO_2 concentration in the atmosphere which is shown in Table 3. It is to be noted that three replicates of soil sample from each test box was tested to capture any variations in results.

2.6. Statistical analysis

Statistical package SPSS 20 (2011) was used for statistical analysis. Significant statistical differences between different data under different CO_2 concentrations were assessed with one-way ANOVA (analysis of variance) analyses, followed by post-hoc Tukey's honestly significant difference (HSD) method (Tukey, 1949; Rosenkrantz, 2009). Correlations were tested using Spearman's rank correlation analysis and regression analysis. Results were considered statistically significant when P-value < 0.1 which corresponds to a 90% confidence interval.

3. Interpretation of test results

3.1. Effects of atmospheric CO_2 on plant characteristics

Figs. 4(a), (b) and 5(a), (b) show the comparison of leaf numbers, LAI, shoot height and root length during three months of growing period under 400 ppm and 1000 ppm CO_2 concentration, respectively where the number after "P" represents CO_2 concentration.

Table 3
Initial and final carbon content (atomic and mass concentration: %) in soil before and after test.

Test	Atomic carbon concentration (%)		Mass carbon concentration (%)	
	Initial	Final	Initial	Final
P400	2.83 ± 0.06	4.93 ± 0.27	1.7 ± 0.04	3 ± 0.15
P1000	2.78 ± 0.08	13.27 ± 0.21	1.76 ± 0.06	6.12 ± 0.09

Fig. 4(a) and (b) show that leaf number and LAI increased significantly in P400 test but did not increase in P1000 test. Growth of new leaves was observed visually under 400 ppm CO_2 concentration (Fig. 4(a)) whereas falling of leaves occurred instead under 1000 ppm CO_2 concentration. In P400 test, leaf number and LAI increased by 32% and 35%, respectively compared to P1000 test. This implies that leaves grow faster under current atmospheric CO_2 concentration rather than under elevated CO_2concentration. But in contrast, Tingey et al. (1996) and Rogers et al. (1992) found better leaf growth under elevated atmospheric CO_2 concentration. Rogers et al. (1992) found a 70% increase of leaf number after 18 days of plant growth in perlite from soybean seeds under 700 ppm CO_2 compared to 350 ppm CO_2 concentration (Fig. 4(a)). Tingey et al. (1996) found a 22% increase of LAI within three months of plant growth from ponderosa-pine seeds in clay-loam soil under 720 ppm CO_2 compared to 365 ppm CO_2 concentration (Fig. 4(b)).

Fig. 5(a) shows that after three months of plant growth, shoot height increased by 21% and 12.5% in P400 and P1000 tests, respectively which implies that shoot height grows faster under current atmospheric CO_2 concentration than elevated CO_2 concentration. But in contrast, Tingey et al. (1996) and Rogers et al. (1992) found better shoot growth under elevated CO_2 concentration. Tingey et al. (1996) found a 6% increase of shoot height within three months of plant growth under 720 ppm CO_2 compared to 365 ppm CO_2 concentration (Fig. 5-(a)). Rogers et al. (1992) found a 15% increase of shoot length within 18 days of plant growth from seeds under 700 ppm CO_2 compared to 350 ppm CO_2 concentration (Fig. 5-(a)). It is noted that, Tingey et al. (1996) and Rogers et al. (1992) used additional nitrogen and Hoagland solution (nutrient enriched solution with high concentration of Nitrogen, Phosphorous and Potassium) in the soil. In this study, no additional nutrient was added to the soil which limits plant response to elevated atmospheric CO_2 concentration. Shoot height and leaves did not grow better under elevated atmospheric CO_2 concentration because some researchers concluded that soil nitrogen (N) scarcity limits plants response to elevated atmospheric CO_2 concentration (Reich et al., 2006; Langley and Megonigal, 2010). In addition, stem and shoot of plants need to uptake nitrogen from soil to grow better (Ng'etich et al., 2013).

Fig. 5-(b) shows that after three months of plant growth, root length in the soil increased by 18% and 11% in P400 and P1000 tests, respectively. This implies that root length grows longer like the shoot height of the plant in Fig. 5-(a) under current atmospheric CO_2 concentration than elevated one. But in contrast, Rogers et al. (1992) found a 110% increase of root length within 18 days of plant growth from seeds under 700 ppm CO_2 compared to 350 ppm CO_2 concentration (Fig. 5-(b)). Since in this study, plant roots were grown in heavily compacted soil (95% RC) using optimum moisture content (12%), root growth was hindered and could not grow deeper (Ng et al., 2014; Beckett et al., 2017). As mentioned previously, Rogers et al. (1992) used Hoagland solution in the soil whereas no additional nutrient was added to the soil in this study. Some researchers found that plant roots under high nutrient condition in soil grow faster under elevated CO_2 concentration i.e., 700 ppm (Bernacchi et al., 2000), 550–700 ppm (Hirano et al., 2012) than current CO_2 concentration (350–400 ppm). Phosphorous is the major nutrient element for plant-root growth and nitrogen mediates phosphorous in plants by utilizing it from soil (Ng'etich et al., 2013). Since the soil used in this study has no phosphorous (Table 2), plant-roots could not grow longer under elevated CO_2 concentration.

From the above-mentioned plant characteristics and their growth rate, plants may need sufficient nutrient elements from soil to grow healthier under elevated CO_2 concentration. Here it is to be noted that, different factors (i.e., light intensity, temperature, irrigation frequency and amount, nutrient) interact with atmospheric CO_2 concentration and affect plant growth (Rogers et al., 1996). However, this study was conducted under identical temperature and light as well as irrigation frequency and amount were similar whereas the soil did not have

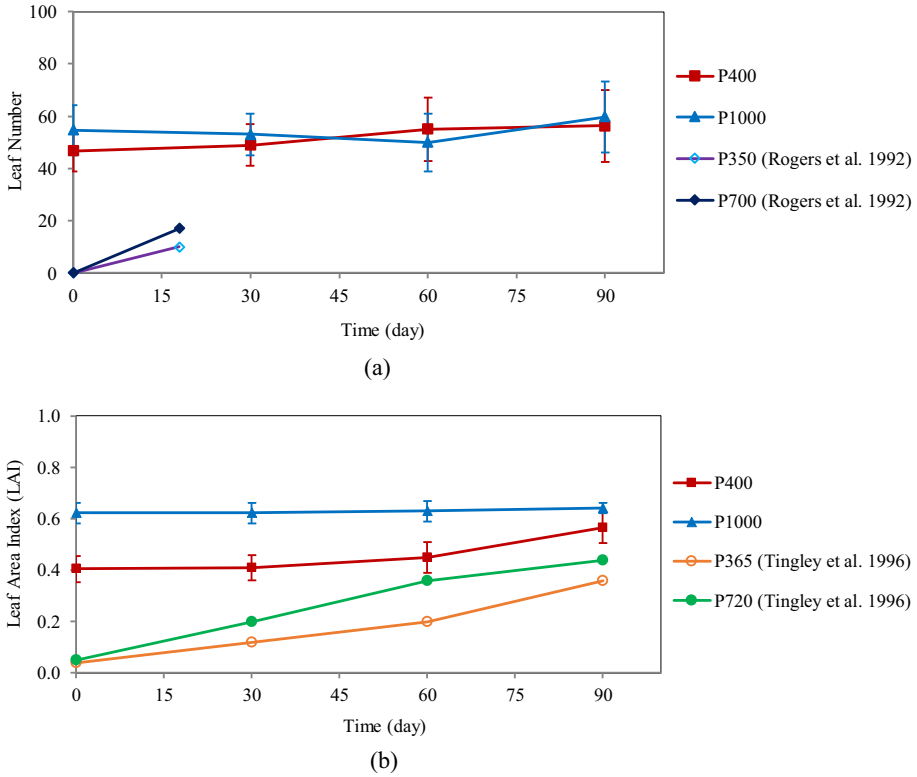

Fig. 4. Measured changes in a) Leaf Number and b) Leaf Area Index (LAI) of plants before transplantation and during growth under different CO_2 concentrations. [Mean values are reported ± standard error of mean (n = 3)].

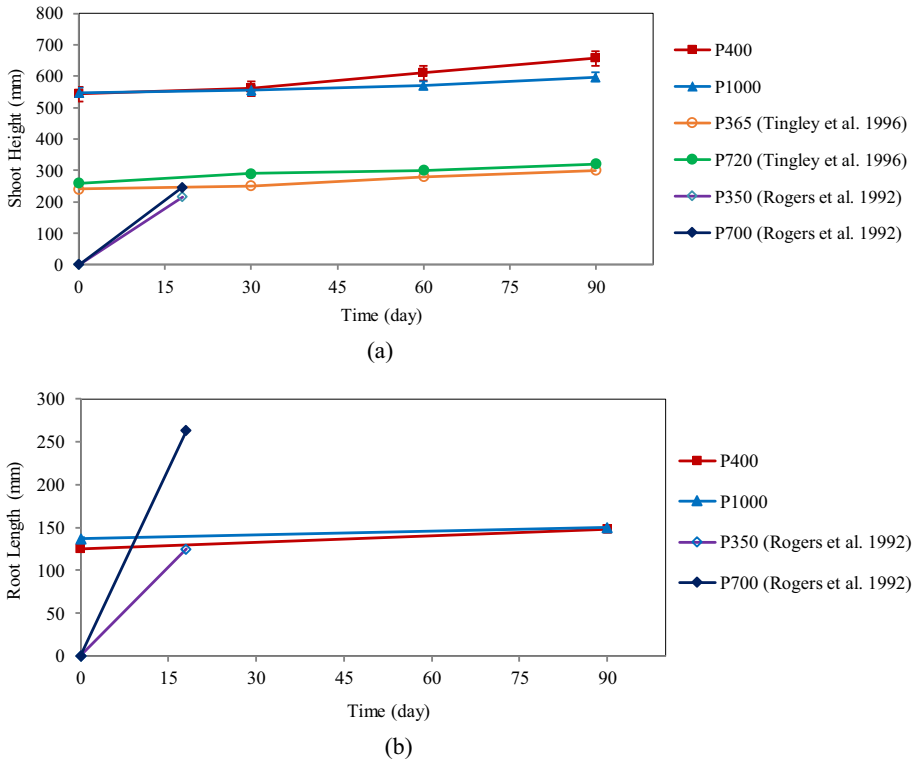

Fig. 5. Measured changes in a) Shoot Height (mm) and b) Root Length (mm) of plants before transplantation and during growth under different CO_2 concentrations. [Mean values are reported ± standard error of mean (n = 3)].

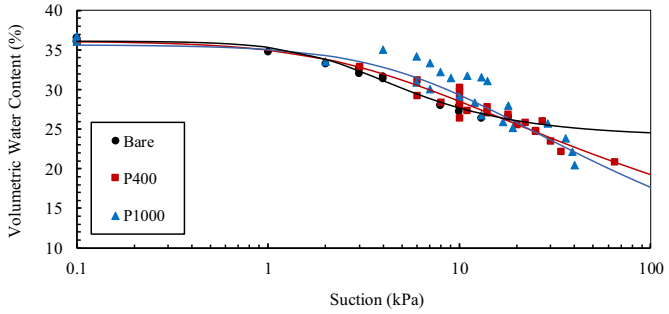

Fig. 6. Measured Soil Water Retention Curves (SWRCs) of bare and vegetated soil along the drying path under 400 ppm and 1000 ppm CO_2 concentrations.

sufficient nitrogen for the plant as shown in Table 2 and CDG soil is generally nutrient poor ((SILTech), 1991). Hence, the plant growth was inhibited due to the deficiency of nutrient interaction with atmospheric CO_2 concentration. The reason behind the growth rate of plants under different CO_2 concentration is also supported by functional-structural (FS) plant model as shown in Fig. 1 (Fourcaud et al., 2008). Based on this model, plants need some basic soil nutrient elements i.e., N, P, K besides air sources i.e., C from atmospheric CO_2 for the better growth and outputs in terms of growth of different plant characteristics i.e., leaf, stem, root. Besides, with no change in the carbon: nitrogen (C:N) ratios of soils (15), the CO_2-only projections require 7.7 to 37.5 Pg of nitrogen and the CO_2-climate projections require 2.3 to 16.9 Pg of nitrogen in the soil for ecosystem response (Hungate et al., 2003). Since CO_2 concentrations are projected to reach levels between 500 and 1000 ppm by 2100 (IPCC, 2013), plants might not thrive in soil with low or no nutrient. This may be detrimental to the plant induced soil suction and hence effectiveness of vegetated slopes, road and railway embankments and landfill covers which will be shown in the next section.

3.2. Effects of atmospheric CO_2 on water retention behaviour of soil

Fig. 6 shows the drying path of the soil water retention curve (SWRC) of bare and vegetated soil under 400 and 1000 ppm CO_2 concentration represented by Bare, P400 and P1000. The SWRCs were obtained by relating the measured VWC to suction during the test from three replicates. Since there were no differences in suction and VWC in bare soil under different CO_2 concentrations, one SWRC was plotted for bare soil considering all data points under both 400 and 1000 ppm CO_2 concentration. Van Genuchten (1980) equation was used to fit the SWRCs and fitting parameters are shown in Table 5. The air-entry value (AEV) of the soil in Bare, P400 and P1000 tests are 1 kPa, 2 kPa and 4 kPa, respectively. Higher water retention and AEV in vegetated soil due to the plant roots were also observed by Leung et al. (2015), which tested the same soil and plant. There are still differences in AEV and water retention ability of soil between P400 and P1000 tests which might be due to the 23% difference in RAI at 80 mm depth (Table 4). Also, soil climate models assume carbon input from vegetation to soil (Karmakar et al., 2016) and previous studies found carbon allocation from plants to soil (Domanski and Kuzyakov, 2000). This carbon allocation was also found from soil when plant root respires CO_2 in the soil

Table 4
Root Area Index (RAI) of plant root along the depth of soil after test.

Depth (mm)	Root Area Index (RAI)	
	P400	P1000
30	0.12 ± 0.014	0.07 ± 0.006
80	0.25 ± 0.014	0.2 ± 0.06
140	0.03 ± 0.002	0.1 ± 0.02

Table 5
Summary of fitting parameters for van Genuchten (1980) equation.

Test	Drying SWRC					
	θ_s (m^3/m^3)	θ_r (m^3/m^3)	α (m^{-1})	n	m	R^2
Bare	0.36	0.00	52.5	1.15	0.13	0.97
P400	0.36	0.00	3.05	1.18	0.15	0.95
P1000	0.36	0.00	9.6	1.33	0.12	0.89

Table 6
Summary of the fitting coefficients (m_o *and* y_o) and adjusted coefficient of determination (R^2) for the linear relationships ($y = y_o + m_o \times x$) given in Figs. 11 and 12.

Relationship	Figure	m_o	y_o	Adj. R^2
Suction against LAI:				
P400	11	69.02	1.26	0.896
P1000	11	24.41	3.48	0.78
Suction against root-shoot ratio:				
P400	12	59.52	1.92	0.74
P1000	12	23.73	5.29	0.44

and microbial utilization of root-borne organic substances occur (i.e., acids) (Domanski and Kuzyakov, 2000). This bio-chemical root activity may also contribute to an increase in water retention ability of soil (Albalasmeh, 2013). In this study, atomic and mass concentration (%) of carbon content in soil increased by 300%–350% in P1000 test (Table 3) which might have increased microbial utilization of root-borne organic acids and hence water retention ability of soil increased under 1000 ppm CO_2 concentration.

3.3. Observed responses of transpiration-induced soil suction and VWC

Figs. 7(a) and (b) show the measured soil suction and VWC during six days of transpiration for bare and vegetated soil at 80 mm depth under 400 ppm and 1000 ppm CO_2 concentration. Since there were no differences in suction and VWC in bare soil under different CO_2 concentrations, average of all data points under both 400 and 1000 ppm atmospheric CO_2 concentration was plotted, represented by “Bare”. P400 and P1000 represent vegetated soil under 400 ppm and 1000 ppm CO_2 concentration, respectively. In Fig. 7(a), soil suction induced by transpiration of plants in vegetated soil increased much more significantly, regardless of CO_2 concentration, than the suction induced in bare soil which is consistent with study by Garg et al. (2015). This is due to water uptake by roots and transpiration through stomata of leaves which induce more suction in vegetated soil than bare soil (Garg et al., 2015). Regarding CO_2 effect, during the first five days, transpiration induced suction had a slight difference (2–5 kPa) between the two CO_2 concentrations. However, as the suction reached the soil field capacity (23–27 kPa), the suction difference increased 10–15 kPa. It is observed that higher plant-induced suction is measured in P400 test than P1000 test after six days of transpiration induced drying test (P-value < 0.1). Elevating current CO_2 concentration (400 ppm) by 600 ppm reduced transpiration induced suction by 20%–40%.

In Fig. 7(b), VWC was higher in bare soil and lower in vegetated soil during six days of transpiration by plants. However, VWC increased by only 2%–5% in soil under 1000 ppm CO_2 concentration after six days of drying compared to the 400 ppm CO_2 concentration (P-value > 0.1).

Similar findings were also observed by previous researchers, Lewis et al. (2002) and Dong-Xiu et al. (2002) found that elevating ambient CO_2 concentration by 200 ppm and 350 ppm in the atmosphere reduced transpiration rate by 12% and 53%–63%, respectively. Despite having differences among previous studies and this study (i.e., environmental condition, duration of study, plant and soil) similar trend was observed that plants were transpiring less water when atmospheric CO_2

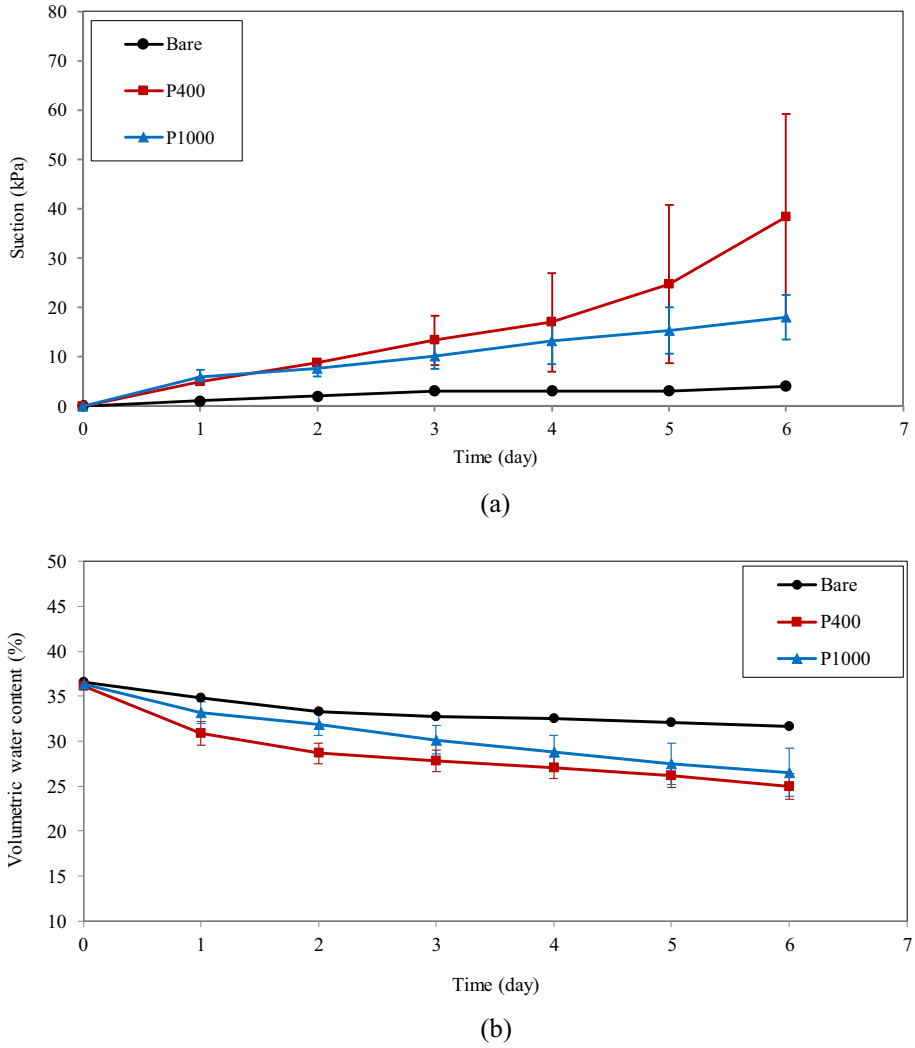

Fig. 7. Measured variations of (a) Suction and (b) VWC with time at a depth of 80 mm during transpiration of plants under 400 ppm and 1000 ppm CO_2 concentrations. [Mean values are reported ± standard error of mean (n = 3)].

concentration was elevated. In contrast, some researchers did not observe significant differences in transpiration rate due to elevated temperature (Apple et al., 2000; Lewis et al., 2002). Generally, plants transpire water through the pores (stomata) in their leaves. During this process, plants lose water through stomata which open to let CO_2 in as well. A principle response of plants to elevated atmospheric CO_2 is to reduce transpired water by decreasing stomatal conductance. A doubling of today's CO_2 levels from 390 ppm to 800 ppm will halve the amount of water lost to the atmosphere (de Boer et al., 2011; Lammertsma et al., 2011). Hence, plant-induced suction decreases and VWC increases during transpiration process of plants under elevated atmospheric CO_2 concentration.

Fig. 8 shows the suction profiles along depth before and after six days of transpiration induced drying. Initial suction profiles of bare and

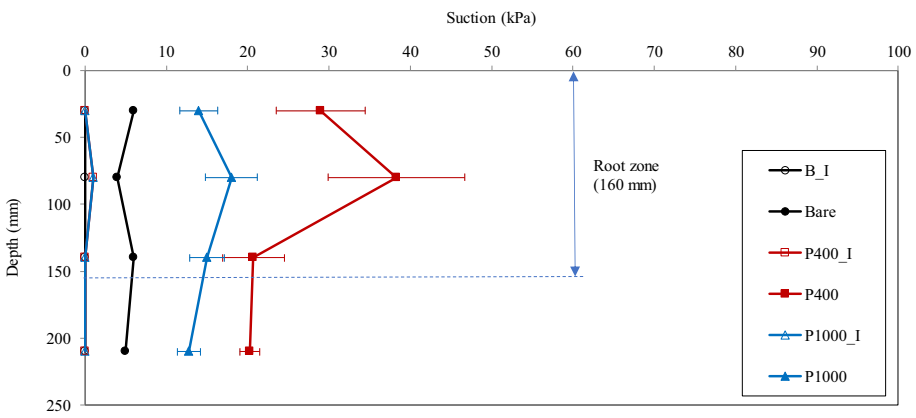

Fig. 8. Measured suction profiles of bare and vegetated soils under 400 ppm and 1000 ppm CO_2 concentrations before and after six days drying in transpiration test. [Mean values are reported ± standard error of mean (n = 3); Comparing between P400 and P1000, *P*-value < 0.1 at 30, 80 and 210 mm depth and *P*-value > 0.1 at 140 mm depth].

vegetated soil under 400 ppm and 1000 ppm CO_2 concentration were represented by Bare_I, P400_I, P1000_I and final suction profiles of them were represented by Bare, P400, P1000, respectively. Since the soil surface was covered, the observed suction increase in bare soil was minimal (4–6 kPa) and distribution of suction was uniform. However, non-uniform suction distribution is observed in vegetated soil due to the RAI distribution (Table 4). Vegetated soil has more suction than bare soil along the root zone (160 mm) because of water uptake by plant roots and water loss through transpiration regardless of CO_2 concentration. In P400 test, the highest suction was at 80 mm depth which is consistent with peak RAI (Table 4) where root water uptake was likely to be greater similar to the study by Garg et al. (2015) where similar soil, soil density (95%) and plant species was used. Ng et al. (2016) also showed that in lower soil density (80%), higher RAI would induce higher suction with the same plant species and soil used in this study. This implies that regardless of soil density, higher RAI induces higher suction as also shown in this study. But in P1000 test, suction profile along the root zone was almost similar. The differences between two suction profiles of P400 and P1000 tests was due to less transpiration of plants under elevated atmospheric CO_2 concentration. The largest suction difference (8–22 kPa) is at 80 mm depth (P-value < 0.1) because of the 23% difference in RAI and effect of CO_2 on plant transpiration. Below the root zone, 10–28 kPa of suction was induced because plant roots did not only lead to the redistribution of suction in root zone, but also at depths below after one week of drying.

3.4. Observed responses of evapo-transpiration-induced soil suction and VWC

Fig. 9(a) and (b) show the measured suction and VWC during four days of evaporation for bare soil and evapo-transpiration for vegetated soil at 80 mm depth under 400 and 1000 ppm CO_2 concentration. Average suction and VWC of bare soil under both CO_2 concentrations were plotted to represent "Bare". P400 and P1000 represent vegetated soil under 400 ppm and 1000 ppm CO_2 concentration, respectively. In Fig. 9(a), suction in bare soil after four days of drying is 18 kPa higher than the suction of bare soil in Fig. 7(a) due to the evaporation by exposed bare surface (P value < 0.1). Induced suction by evapo-transpiration in vegetated soil increased much more significantly, regardless of CO_2 concentration, than the suction in bare soil because of plants. Regarding CO_2 effect, during first two days, evapo-transpiration induced suction had a slight difference (3–7 kPa) between the two CO_2 concentration. However, similar to the transpiration induced drying (Fig. 7(a)), as the suction reached the field capacity (23–27 kPa), suction difference increased 10–24 kPa after four days of drying (P value < 0.05 < 0.1). It is also observed that higher suction was measured in P400 test rather than in P1000 test after four days of evapo-transpiration induced drying. Elevating current CO_2 concentration (400 ppm) by 600 ppm reduced evapo-transpiration induced suction by 28%–50%.

In Fig. 9(b), only 3%–5% difference was observed between bare and vegetated soil during first two days which was also observed in Fig. 7 during six days of transpiration induced drying. However, the VWC was

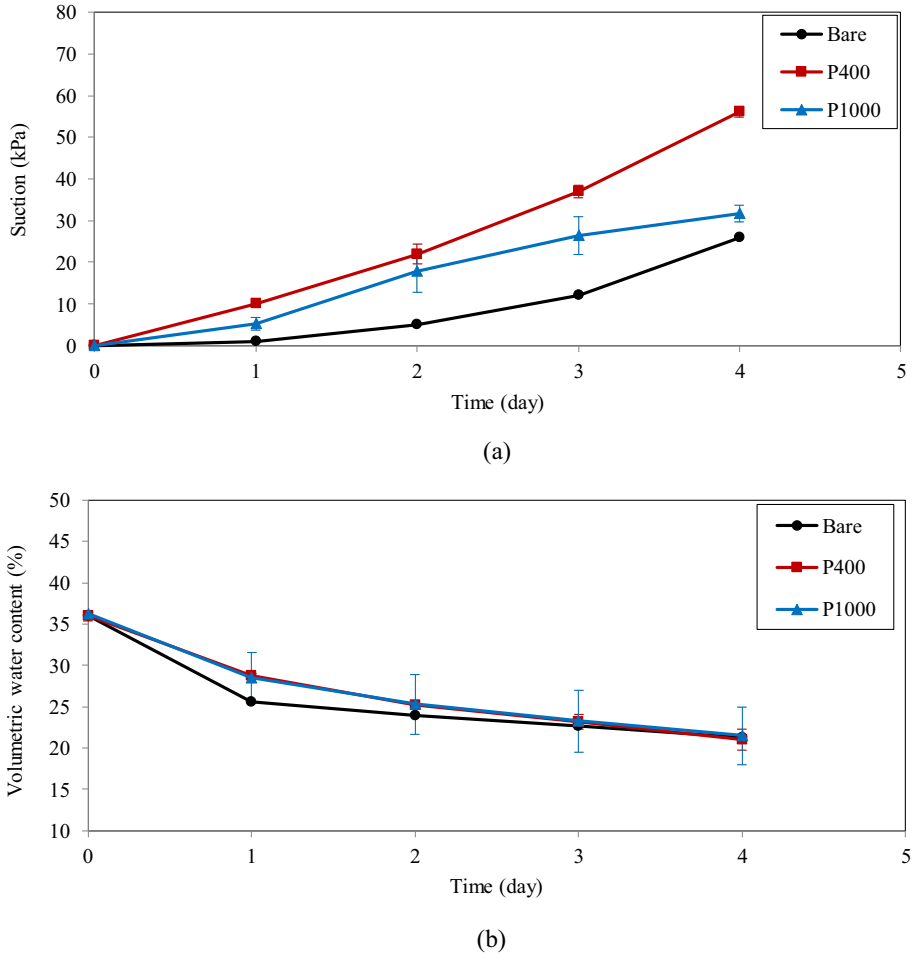

Fig. 9. Measured variations in (a) suction and (b) VWC with time at a depth of 80 mm during evaporation of bare surface and transpiration of plants under 400 ppm and 1000 ppm CO_2 concentrations. [Mean values are reported ± standard error of mean (n = 3)].

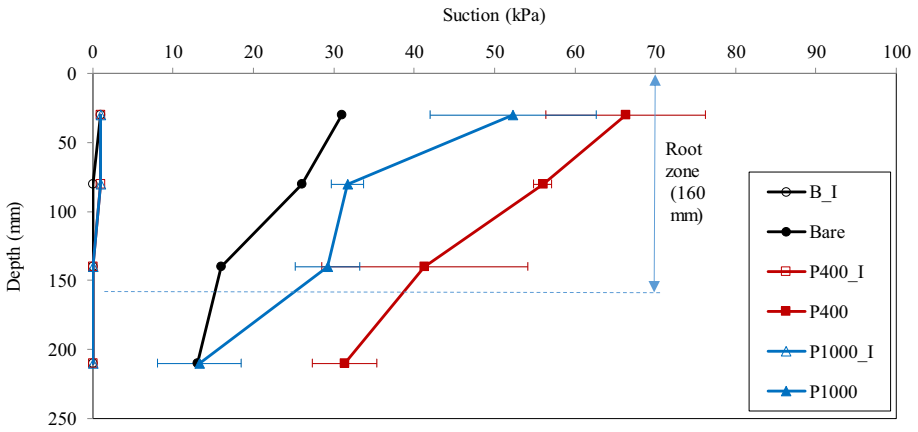

Fig. 10. Measured suction profiles of bare and vegetated soils under 400 ppm and 1000 ppm CO_2 concentrations before and after four days drying in evapotranspiration test. [Mean values are reported ± standard error of mean (n = 3); Comparing between P400 and P1000, *P*-value < 0.05 < 0.1 at 80 and 210 mm depth and *P*-value > 0.1 at 30 and 140 mm depth].

the same for both bare and vegetated soil after four days where no significant differences were observed (*P*-value > 0.1). The large (3%–4%) deviations in vegetated soil implies that VWC variations in the replicates were significant. Since the probes measure VWC in a volume of soil and not at a specific depth like soil suction, different water content and organic content in soil pores might have influenced the soil pore structures as discussed previously in Fig. 6. This might have affected the VWC measurements. In addition, the observed error (± 3%) during the calibration of probes might also have affected the results.

Similar findings due to evapo-transpiration were also observed by previous researchers that, elevating ambient CO_2 concentration by 320–350 ppm reduced evapo-transpiration rate by 10%–19% (Hungate et al., 2002; Dijkstra et al., 1999; Grunzweig and Korner, 2001). Again, a similar trend is observed that plants are transpiring less water when atmospheric CO_2 concentration is elevated. Thus, evapo-transpiration induced suction also decreases. However, in a different soil (calcareous soil), Bucher-Wallin et al. (2000) did not observe significant differences in evapo-transpiration rate under elevated atmospheric CO_2 concentration.

Fig. 10 shows the suction profiles along depth due to evapo-transpiration before and after four days of drying. Initial suction profiles of bare and vegetated soil under 400 ppm and 1000 ppm CO_2 were represented by Bare_I, P400_I, P1000_I and final suction profiles of them were represented by Bare, P400, P1000, respectively. Since soil surface was exposed to the atmosphere, suction induced at shallow depth (30 mm) in bare and vegetated soil was higher than those at deeper depths in contrast to Fig. 8 due to the hydraulic gradient established at the soil–atmosphere interface during surface evaporation which was relatively higher. In both P400 and P1000 tests, due to the water demand at shallow depths (30 mm and 80 mm) the suction was higher at 140 mm and 210 mm depths though the RAI was either small or negligible (Table 4). There is an obvious difference between suction profiles in P400 and P1000 test due to elevated CO_2 concentration and less evapo-transpiration by the plant-soil system since LAI was similar in both tests. The difference was the highest (25 kPa) at 80 mm depth due to both 23% difference in RAI (Table 4) and CO_2 effect on plant transpiration (*P*-value < 0.1). In both transpiration and evapo-transpiration induced drying tests (Fig. 8 and Fig. 10), the major difference of the trend was within 30 to 140 mm depth. The suction difference between P400 and P1000 test, was low at 30 mm depth, then increased at 80 mm depth and again decreased at 140 mm depth. This might be due to high RAI (large root surface area) within this zone (Table 4) indicating retained water in soil due to less transpiration by plants in P1000 test and held by the root surface.

Garg et al. (2015) concluded in controlled laboratory test without supplying additional CO_2 in the atmosphere that, evapo-transpiration induced suction will be higher than transpiration induced suction. As mentioned in the previous sections, leaf area growth was hindered due to higher atmospheric CO_2 concentration in nutrient poor soil which exposed more bare soil surface which should have increased the soil suction. On the other hand, transpired water amount reduced because of the low stomatal conductance of leaves due to absorbing CO_2 which must have reduced the soil suction as explained in Figs. 7-(a) and 8. Since the LAI was similar (Fig. 4-(b)) in both tests P400 and P1000, the net evapo-transpiration induced soil suction reduced around 14–25 kPa (28–50%) under 1000 ppm CO_2 concentration considering the competing phenomena mentioned above. However, this study implies that both transpiration and evapo-transpiration induced soil suction will be reduced when atmospheric CO_2 concentration will be elevated (*P*-value < 0.1).

3.5. Atmospheric CO_2 effect on correlation between plant traits and plant induced soil suction

Figs. 11 and 12 show the correlation of leaf area index (LAI) and root-shoot biomass ratio with plant induced peak soil suction under 400 ppm and 1000 ppm CO_2 concentration. These plant traits were chosen because a positive linear correlation of LAI (Ng et al., 2016) and root-shoot biomass ratio (Boldrin et al., 2017) with plant induced corresponding peak soil suction were observed. Data from bare soil are also plotted by considering a zero value of LAI and root-shoot biomass ratio to represent a fair comparison between P400 and P1000 test. Here P400 and P1000 represent the plants grown under treatment of 400 ppm and 1000 ppm CO_2 concentration, respectively. Statistical and regression analysis were thus conducted to capture the differences in different treatments as well as to capture the correlations of the replicates. Linear regressions of all data points from all replicates are given in Table 6 for the correlations under 400 ppm and 1000 ppm CO_2 concentration.

Fig. 11 shows that in P400 and P1000 tests, LAI was within a range of 0.5–0.7 with plant-induced peak soil suction of 28–55 kPa and 12–25 kPa, respectively. A higher LAI means more leaf surface area which have more stomata on tree leaves to receive more energy for transpiration (Kelliher et al., 1995). Though having a similar range of LAI, due to elevated atmospheric CO_2 concentration, plant-induced suction was lower in P1000 test. This is because leaves cannot transpire enough water because of decreasing stomatal conductance under elevated atmospheric CO_2 concentration (de Boer et al., 2011; Lammertsma et al., 2011). The linear correlation was significantly higher (R^2 = 0.93) and slope of the correlation was steeper (69) in P400 test (*P*-value < 0.05 < 0.1) as opposed to the P1000 test (R^2 = 0.85) where slope (24.4) was 2.8 times lower (*P*-value < 0.1). Strong positive linear correlation (R^2 = 0.90) and steeper slope (42) between LAI and induced suction were also found in plants under current atmospheric condition (380–400 ppm CO_2) after two days of

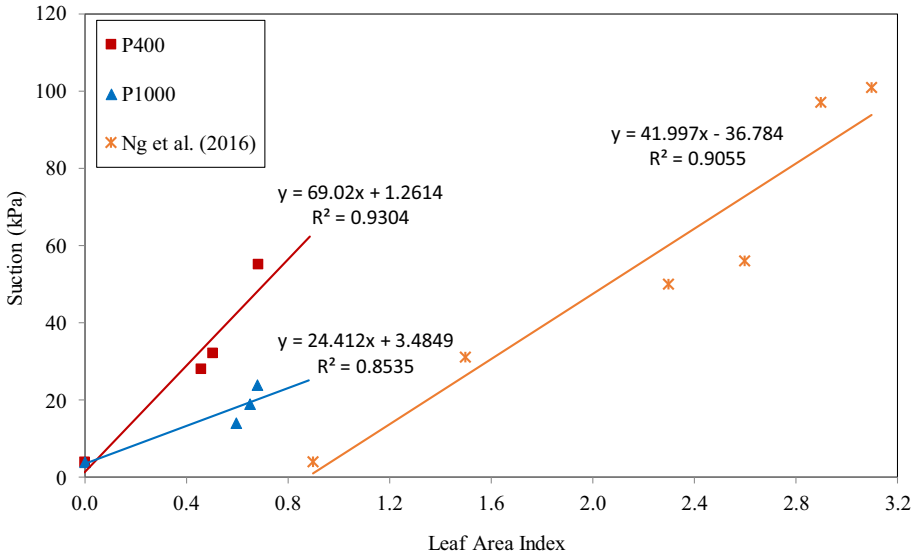

Fig. 11. Relationship of leaf area index (LAI) with matric suction (kPa) under 400 ppm and 1000 ppm CO_2 concentrations. [Linear regressions of all data points from all replicates are given in Table 6. Solid lines represent the trends in the relationships between LAI and soil suction (Table 6). Spearman's rank correlation analysis between LAI and soil suction of all plants under 400 ppm and 1000 ppm CO_2 concentration was performed. For P400, r = 0·965 and P-value = 0.035 < 0.05 < 0·1; For P1000, r = 0·924 and P-value = 0.076 < 0·1.]

drying by Ng et al. (2016) (Fig. 11), where same plant species, soil type and density were used. This implies that, despite having similar LAI, the rate of induced suction will decrease under increasing atmospheric CO_2 concentration due to low stomatal conductance of leaves and hence low transpiration by leaves.

Fig. 12 shows that, in P400 test, root-shoot biomass ratio ranged 0.55–0.7 and induced corresponding suction ranged 28–55 kPa. Meanwhile, root-shoot ratio ranged 0.48–0.6 and induced corresponding suction ranged 12–25 kPa in P1000 test. The linear correlation between root-shoot biomass ratio and its induced suction was significantly stronger (R^2 = 0.83) in P400 test (P-value < 0.1) as opposed to the P1000 test (R^2 = 0.62) (P-value > 0.1). This relationship in P400 test implies that higher root-shoot biomass ratio will induce higher suction because increase in root-shoot ratio allow the plant to extract more water (Stulen and Hertog, 1993). However, under 1000 ppm CO_2 concentration, root-shoot biomass ratio was not that larger because roots could not grow healthier due to lack of N, P, K elements in soil stated in Figs. 1 and 5(b). Hence, roots could not uptake much water and shoot could not transport and transpire enough water under increasing CO_2 compared to the current atmospheric CO_2 concentration. Also, linear correlation (R^2 = 0.65) was found between root-shoot biomass ratio and induced suction (Fig. 12) by Boldrin et al. (2017).

Since ten different plant species and their induced suction during different durations were plotted, Boldrin et al. (2017) could not observe strong relationship like Ng et al. (2016) observed (Fig. 11) because it only investigated a single tree species. Despite the difference, slope of the linear regression was steeper (93) like the slope in P400 test in this study (59.5). This implies that plants with higher root-shoot biomass ratio will induce higher soil suction. However, in P1000 test, slope (23.7) of regression line was 2.5 times lower than the slope observed in the relationship in P400 test in Fig. 12. This implies that, the induced suction will decrease under increasing atmospheric CO_2 concentration even if the LAI and root-shoot biomass ratio increase.

This reduction of plant induced soil suction might have a detrimental effect to the design of vegetated slopes, roads and railway embankments and landfill covers.

4. Summary and conclusions

This study explores the effects of current atmospheric CO_2 (400 ppm) and predicted CO_2 (1000 ppm) within year 2100 on three replicates of *Schefflera heptaphylla* (Ivy tree) and induced soil suction and VWC in heavily compacted (95% RC) silty sand. Two test series were conducted to grow the plants under 400 ppm and 1000 ppm CO_2 concentration for three months. In both tests, transpiration induced

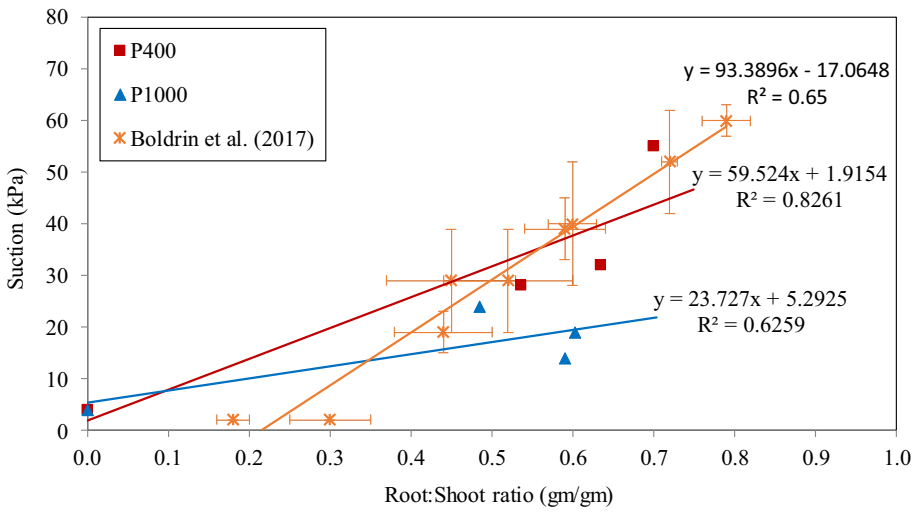

Fig. 12. Relationship of root-shoot biomass ratio (gm/g) with matric suction (kPa) under 400 and 1000 ppm CO_2 concentrations. [Linear regressions of all data points from all replicates are given in Table 6. Solid lines represent the trends in the relationships between root-shoot biomass ratio and soil suction (Table 6). Spearman's rank correlation analysis between root-shoot biomass ratio and soil suction of all plants under 400 ppm and 1000 ppm CO_2 concentration was performed. For P400, r = 0·909 and P-value = 0.09 < 0·1; For P1000, r = 0·79 and P-value = 0.21 > 0·1.]

drying (6 days) and evapo-transpiration induced drying (4 days) were done to investigate soil suction and VWC. This study also explores the correlation of plant traits (i.e., LAI and root-shoot biomass ratio) with corresponding induced peak soil suction under 400 and 1000 ppm CO_2 concentration.

From this study, it is revealed that plants growing in nutrient poor silty sand (CDG) can survive but inhibits growth under elevated CO_2 concentration. Under current atmospheric CO_2 concentration (400 ppm), shoot height, root length, leaf number and LAI of plants increased by 10%, 7%, 32% and 35%, compared to the elevated CO_2 concentration (1000 ppm). This is because plants might need more nutrients in soil to metabolize the effects of up-taking more CO_2 from the atmosphere.

Elevated atmospheric CO_2 concentration reduced plant transpiration induced soil suction after six days of drying by 10–22 kPa (20%–40%) and reduced evapo-transpiration induced soil suction after four days of drying by 14–25 kPa (28%–50%). This is because leaves cannot open their stomata wide enough and hence transpire less water when atmospheric CO_2 concentration is elevated.

Air entry value (AEV) and soil water retention behaviour of vegetated soil were also changed due to the difference in RAI and elevated atmospheric CO_2 concentration. AEV increased to 4 kPa indicating improved water retention ability of soil under elevated atmospheric CO_2 concentration (1000 ppm). This might be due to the microbial utilization of root-borne organic acids which occurred due to the increased carbon content input from plants to soil.

This study also shows that after three months of plant growth, LAI and root-shoot biomass ratio have a strong positive linear correlation (R^2 = 0.8–0.9; P-value < 0.1) with plant induced soil suction for 400 ppm CO_2 concentration but rather weak correlation (R^2 = 0.6–0.8; P-value > 0.1) for 1000 ppm CO_2 concentration. Due to elevated atmospheric CO_2 concentration, leaves keep their stomata slightly open and thus reduces the rate of transpiration. Therefore, induced suction in vegetated soil decreased significantly. Hence, the correlation between plant characteristics (LAI and root-shoot ratio) and soil suction became weaker under 1000 ppm CO_2 concentration compared to the 400 ppm CO_2 concentration.

Also, root-shoot biomass ratio was lower which leads to lower induced suction and weak correlation under 1000 ppm CO_2 concentration. This is because roots could not grow healthier due to lack of N, P, K elements in soil hence roots could not uptake much water and thus shoot could not transport and transpire enough water under increasing CO_2 concentration compared to the current atmospheric CO_2 concentration.

In this study, significant differences were observed in vegetated soil suction and soil water retention behaviour under different atmospheric CO_2 concentrations. This implies that, the effect of atmospheric CO_2 concentration on plant induced soil suction must be considered for conservative design of vegetated soil slopes, road and railway embankments and landfill covers. Given the relatively shallow depth of the test boxes used in the experiments, research findings from this study should be treated with caution. Ideally more large-scale experiments may be carried out.

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References

Albalasmeh, A.A., 2013. Biophysical Controls on Rhizosphere Dynamics. University of California, Merced, CA, USA (PhD thesis).
Apple, M.E., Olszyk, D.M., Ormrod, D.P., Lewis, J., Southworth, D., Tingey, D.T., 2000. Morphology and stomatal function of Douglas fir needles exposed to climate change: elevated CO_2 and temperature. Int. J. Plant Sci. 161, 127–132.
ASTM, 2010. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). American Society for Testing and Materials, West Conshohocken, PA, USA.
Beckett, C.T.S., Glenn, D., Bradley, K., Guzzomi, A.L., Merritt, D., Fourie, A.B., 2017. Compaction conditions greatly affect growth during early plant establishment. Ecol. Eng. 106, 471–481.
Bernacchi, C.J., Coleman, J.S., Bazzaz, F.A., McConnaughay, K.D.M., 2000. Biomass allocation in old-field annual species grown in elevated CO_2 environments: no evidence for optimal partitioning. Glob. Chang. Biol. 6, 855–863.
de Boer, H.J., Lammertsma, E.I., Wagner-Cremer, F., Dilcher, D.L., Wassen, M.J., Dekker, S.C., 2011. Climate forcing due to optimization of maximal leaf conductance in subtropical vegetation under rising CO_2. Proc. Natl. Acad. Sci. 108 (10), 4041–4046.
Boldrin, D., Leung, A.K., Bengough, A.G., 2017. Correlating hydrologic reinforcement of vegetated soil with plant traits during establishment of woody perennials. Plant Soil 410, 1–15.
Bucher-Wallin, I.K., Sonnleitner, M.A., Egli, P., Gunthardt-Goerg, M.S., Tarjan, D., Schulin, R., Bucher, J.B., 2000. Effects of elevated CO_2, increased nitrogen deposition and soil on evapo-transpiration and water use efficiency of spruce-beech model ecosystems. Phyton 40, 49–60.
Conley, M.M., Kimball, B.A., Brooks, T.J., Pinter Jr., P.J., Hunsaker, D.J., Wall, G.W., Adams, N.R., LaMorte, R.L., Matthias, A.D., Thompson, T.L., Leavitt, S.W., Ottman, M.J., Cousins, A.B., Triggs, J.M., 2001. CO_2 enrichment increases water-use efficiency in sorghum. New Phytol. 151, 407–412.
Dijkstra, P., Schapendonk, A.H.M.C., Groenwold, K., Jansen, M., Van de Geijn, S.C., 1999. Seasonal changes in the response of winter wheat to elevated atmospheric CO_2 concentration grown in open-top chambers and field tracking enclosures. Glob. Chang. Biol. 5, 563–576.
Dlugokencky, E., Tans, P., 2018. NOAA/ESRL. https://www.esrl.noaa.gov/gmd/ccgg/trends/, Accessed date: 10 May 2018.
Domanski, G., Kuzyakov, Y., 2000. Carbon input by plants into the soil. Review. J. Plant Nutr. Soil Sci. 163, 421–431.
Dong-Xiu, W., Gen-Xuan, W., Yong-Fei, B., Jian-Xiong, L., Hong-Xu, R., 2002. Response of growth and water use efficiency of spring wheat to whole season CO_2 enrichment and drought. Acta Bot. Sin. 44, 1477–1483.
Dugas, W.A., Polley, H.W., Mayeux, H.S., Johnson, H.B., 2001. Acclimation of whole-plant *Acacia farnesiana* transpiration to carbon dioxide concentration. Tree Physiol. 21, 771–773.
Fourcaud, T., Zhang, X., Stokes, A., Lambers, H., Korner, C., 2008. Plant growth modelling and applications: the increasing importance of plant architecture in growth models. Ann. Bot. 101, 1053–1063.
Francour, P., Semroud, R., 1992. Calculation for the root area index in *Posidonia oceanica* in the western Mediterranean. Aquat. Bot. 42 (3), 281–286.
Fredlund, D.G., Rahardjo, H., 1993. Soil Mechanics for Unsaturated Soils. John Wiley & Sons, New York.
Garg, A., Leung, A.K., Ng, C.W.W., 2015. Comparisons of soil suction induced by evapotranspiration and transpiration of *Schefflera heptaphylla*. Can. Geotech. J. 52 (12), 2149–2155.
Gates, D.M., 1980. Biophysical Ecology. Springer-Verlag, New York, NY, USA.
GCO (Geotechnical Control Office), 2000. Geotechnical manual for slopes. Geotechnical Control Office, Hong Kong, China.
GEO (Geotechnical Engineering Office), 2011. Technical Guidelines on Landscape Treatment for Slopes. Geotechnical Engineering Office, Hong Kong, China.
Grunzweig, J.M., Korner, C., 2001. Growth, water and nitrogen relations in grassland model ecosystems of the semi-arid Negev of Israel exposed to elevated CO_2. Oecologia 128, 251–262.
Hau, B.C.H., Corlett, R.T., 2003. Factors affecting the early survival and growth of native tree seedlings planted on a degraded hillside grassland in Hong Kong, China. Restor. Ecol. 11 (4), 483–488.
Hirano, A., Hongo, I., Koike, T., 2012. Morphological and physiological responses of Siebold's beech (*Fagus crenata*) seedlings grown under CO_2 concentrations ranging from pre-industrial to expected future levels. Landsc. Ecol. Eng. 8, 59–67.
Hungate, B.A., Reichstein, M., Dijkstra, P., Johnson, D., Hymus, G., Tenhunen, J.D., Hinkle, C.R., Drake, B.G., 2002. Evapo-transpiration and soil water content in a scrub-oak woodland under carbon dioxide enrichment. Glob. Chang. Biol. 8, 289–298.
Hungate, B.A., Dukes, J.S., Shaw, M.R., Luo, Y.Q., Field, C.B., 2003. Nitrogen and climate change. Science 302, 1512–1513.
IPCC, 2013. Climate Change 2013. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. pp. 1535.
Karmakar, R., Das, I., Dutta, D., Rakshit, A., 2016. Potential effects of climate change on soil properties: a review. Forensic Sci. Int. 4, 51–73.
Keeling, C.D., Whorf, T.P., 2005. Atmospheric CO_2 records from sites in the SIO air sampling network. In: Trends: A Compendium of Data on Global change. Carbon Dioxide Information Analysis. Ctr., Oak Ridge Natl. Lab., U.S. Dep. of Energy, Oak Ridge, TN.
Kelliher, F.M., Leuning, R., Raupach, M.R., Schulze, E.D., 1995. Maximum conductances for evaporation from global vegetation types. Agric. For. Meteorol. 73, 1–16.
Krahn, J., Fredlund, D.G., 1972. On total, matric and osmotic suction. Soil Sci. 114 (5), 339–348.
Lammertsma, E.I., de Boer, H.J., Dekker, S.C., Dilcher, D.L., Lotter, A.F., Wagner-Cremer, F., 2011. Global CO_2 rise leads to reduced maximum stomatal conductance in Florida vegetation. Proc. Natl. Acad. Sci. 108 (10), 4035–4040.
Langley, J.A., Megonigal, J.P., 2010. Ecosystem response to elevated CO_2 levels limited

by nitrogen-induced plant species shift. Nature 466, 96–99.
Leung, A.K., Garg, A., Ng, C.W.W., 2015. Effects of plant roots on soil-water retention and induced suction in vegetated soil. Eng. Geol. 193, 183–197.
Lewis, J.D., Lucash, M., Olszyk, D.M., Tingey, D.T., 2002. Stomatal responses of Douglas-fir seedlings to elevated carbon dioxide and temperature during the third and fourth years of exposure. Plant Cell Environ. 25, 1411–1421.
Liang, Y.M., Hazlett, D.L., Lauenroth, W.K., 1989. Biomass dynamics and water use efficiencies of five plant communities in the shortgrass steppe. Oecologia 80 (2), 148–153.
Ng, C.W.W., Leung, A.K., 2012. Measurements of drying and wetting permeability functions using a new stress-controllable soil column. J. Geotech. Geoenviron. 138, 58–65.
Ng, C.W.W., Menzies, B., 2007. Advanced Unsaturated Soil Mechanics and Engineering. Taylor and Francis, USA.
Ng, C.W.W., Leung, A.K., Woon, K.X., 2014. Effects of soil density on grass-induced suction distributions in compacted soil subjected to rainfall. Can. Geotech. J. 51 (3), 311–321.
Ng, C.W.W., Garg, A., Leung, A.K., Hau, B.C.H., 2016. Relationships between leaf and root area indices and soil suction induced during drying–wetting cycles. Ecol. Eng. 91, 113–118.
Ng'etich, Niyokuri, N., O.K.A., Rono, J.J., Fashaho, A., Ogweno, J.O., 2013. Effect of different rates of nitrogen fertilizer on the growth and yield of zucchini (Cucurbita pepo cv. Diamant L.) Hybrid F1 in Rwandan high-altitude zone. Int. J. Agric. Crop Sci. 5 (1), 54–62.
Prior, S.A., Rogers, H.H., Runion, G.B., Hendrey, G.R., 1994. Free-air CO_2 enrichment of cotton: vertical and lateral root distribution patterns. Plant Soil 165, 33–44.
Rasband, W.S., 2011. ImageJ. Bethesda, MD, USA, US National Institutes of Health.
Reich, P.B., et al., 2006. Nitrogen limitation constrains sustainability of ecosystem response to CO_2. Nature 440, 922–925.
Rogers, H.H., Peterson, C.M., McCrimmon, J.N., Cure, J.D., 1992. Response of plant roots to elevated atmospheric carbon dioxide. Plant Cell Environ. 15 (6), 749–752.
Rogers, H.H., Prior, S.A., Runion, G.B., Mitchell, R.J., 1996. Root to shoot ratio of crops as influenced by CO_2. Plant Soil 187, 229–248.
Rosenkrantz, W.A., 2009. Introduction to Probability and Statistics for Science, Engineering, and Finance. Taylor & Francis Group, Florida.
Shen, P., Zhang, L.M., Chen, H.X., Gao, L., 2017. Role of vegetation restoration in mitigating hillslope erosion and debris flows. Eng. Geol. 216, 122–133.
Sinnathamby, G., Phillips, D.H., Sivakumar, V., Paksy, A., 2013. Landfill cap models under simulated climate change precipitation: impacts of cracks and root growth. Géotechnique 64 (2), 95–107.
Smethurst, J.A., Briggs, K.M., Powrie, W., Ridley, A., Butcher, D.J.E., 2015. Mechanical and hydrological impacts of tree removal on a clay fill railway embankment. Géotechnique 65 (11), 869–882.
SPSS 20, 2011. Statistical Analysis Software (Standard Version). SPSS Inc.
Standing Inter-Departmental Landscape Technical Group, Hong Kong (SILTech), 1991. Tree Planting and Maintenance in Hong Kong.
Stulen, I., Hertog, J.D., 1993. Root growth and functioning under atmospheric CO_2 enrichment. Plant Ecol. 104 (1), 99–115.
TDOT (Tennessee Department of Transportation), 1981. Subgrade Construction and Preparation: Specifications for Road and Bridge construction. Tennessee Department of Transportation (TDOT) Bureau of Highways, Kingsport, TN, USA.
Tingey, D.T., Johnson, M.G., Phillips, D.L., Johnson, D.W., Ball, J.T., 1996. Effects of elevated CO_2 and nitrogen on the synchrony of shoot and root growth in ponderosa pine. Tree Physiol. 16, 905–914.
Tukey, J.W., 1949. Comparing individual means in the analysis of variance. Biometrics 5 (2), 99–114.
Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44 (5), 892–898.
Veihmeyer, F.J., Hendrickson, A.H., 1931. The moisture equivalent as a measure of the field capacity of soils. Soil Sci. 32 (3), 181–193.
Watson, D.J., 1947. Comparative physiological studies on the growth of field crops: I. Variation in net assimilation rate and leaf area between species and varieties and within and between years. Ann. Bot. 11 (1), 41–76.
Wullschleger, S.D., Norby, R.J., 2001. Sap velocity and canopy transpiration in a sweetgum stand exposed to free-air CO_2 enrichment (FACE). New Phytol. 150, 489–498.

List of symbols

Cfm: cubic feet per minute
D10: grain diameter at 10% passing
D30: grain diameter at 30% passing
D60: grain diameter at 60% passing
P: Plant
Pg: Peta-gram (1015 gm)
ppm: parts per million
m: fitting parameter in van Genuchten's equation (van Genuchten, 1980)
n: fitting parameter in van Genuchten's equation (van Genuchten, 1980)
α: fitting parameter in van Genuchten's equation (van Genuchten, 1980)
θr: residual volumetric water content
θs: saturated volumetric water content
mo, yo: fitting coefficients